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Design and Delivery of a Filter for Removal of Siloxanes from the ISS Atmosphere

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Dimethylsilanediol (DMSD) has been identified as a problematic chemical contaminant aboard ISS. This contaminant was initially identified in the ISS condensate and in the Water Processor Assembly (WPA) product water in 2010 when an increasing total organic carbon (TOC) trend was detected in the water produced by the WPA. DMSD is not a crew health hazard at the levels observed in the product water, but it may degrade the performance of the Oxygen Generation System (OGS) which uses product produced by the WPA for electrolysis. In addition, DMSD can prevent the effective operation of the WPA catalytic reactor, and necessitates early replacement of Multifiltration Beds in the WPA. An investigation into the source of DMSD has determined that polydimethylsiloxanes (PDMSs) are hydrolyzing in the Condensing Heat Exchanger (CHX) to form DMSD. PDMSs are prevalent aboard ISS from a variety of sources, including crew hygiene products, adhesives, caulks, lubricants, and various nonmetallics. TPMSs are also implicated in CHX hydrophilic coating degradation, rendering it hydrophobic and adversely affecting its ability to effectively transmit water to the condensate bus. Eventually this loss in performance results in water droplets in the air flow out of the CHX core, which can lead to microbial growth in the air ducts and can impact the performance of downstream systems. Design concepts have now been developed for removing PDMS in the air stream before it can reach the CHX core, thus preventing degradation of the coating and decomposition of the PDMS to DMSD. This paper summarizes the current status of the effort to deliver filters to ISS for removing PDMSs from the atmosphere before they can adversely impact the performance of the CHX coating and the WPA.

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Nomenclature

<i>AQM</i>	=	Air Quality Monitor
<i>BFE</i>	=	Bacteria Filter Element
<i>CCAA</i>	=	Common Cabin Air Assembly
<i>CHX</i>	=	condensing heat exchanger
<i>CTB</i>	=	cargo transfer bag
<i>D3</i>	=	hexamethylcyclotrisiloxane
<i>D4</i>	=	octamethylcyclotetrasiloxane
<i>D5</i>	=	decamethylcyclopentasiloxane
<i>DMSD</i>	=	dimethylsilanediol
<i>EDU</i>	=	Engineering Development Unit
<i>ECLS</i>	=	environmental control and life support
<i>ePTFE</i>	=	expanded polytetrafluoroethylene
<i>GRC</i>	=	Glenn Research Center
<i>HEPA</i>	=	high efficiency particulate arrestance
<i>KSC</i>	=	Kennedy Space Center
<i>MMST</i>	=	monomethylsilanetriol
<i>PAO</i>	=	polyalphaolefin
<i>PDMS</i>	=	polydimethylsiloxane
<i>PTFE</i>	=	polytetrafluoroethylene
<i>TMS</i>	=	trimethylsilanol
<i>UTAS</i>	=	United Technologies Aerospace Systems
<i>WPA</i>	=	Water Processor Assembly
<i>cL</i>	=	centiliter
<i>g</i>	=	gram
<i>L</i>	=	liter
<i>m</i>	=	meter
<i>mg</i>	=	milligram
<i>mL</i>	=	milliliter
<i>Pa</i>	=	Pascal
<i>μm</i>	=	micrometer

I. Introduction

DIMETHYLSILANEDIOL (DMSD) is a common by-product of polydimethylsiloxane (PDMS) compound degradation. PDMSs, also referred to as siloxanes, are common compounds present in various products, including caulks, adhesives, lubricants, and hygiene products. Atmospheric grab samples and data from the on-orbit Air Quality Monitor (AQM) show that various PDMS compounds are prevalent at sustained concentrations in the ISS cabin environment. Analysis of condensate samples from ISS show that DMSD has been present in the Water Processor Assembly (WPA) waste water since WPA operations began aboard ISS. Ground testing and analysis of on-orbit data show that DMSD eventually saturates the Multifiltration Beds and is only partially removed by the Catalytic Reactor. As a result, it eventually increases in the potable water to the point that replacement of the Multifiltration Beds is required to maintain potable water quality.

To prevent DMSD from impacting potable water quality, engineering personnel are developing a method to reduce DMSD concentrations to manageable levels in the condensate by removing the siloxanes in the cabin atmosphere. This removal step would occur prior to each Condensing Heat Exchanger (CHX) in the U.S. Laboratory Module, Node 2, and Node 3.

II. Correlation between Airborne PDMS Species and DMSD in Humidity Condensate

Evaluating the degree of correlation between siloxane concentrations and DMSD observed in humidity condensate provides interesting insight into the interplay and dynamics between the cabin environment and humidity condensate loading. Both visual inspection of data trending plots and statistical evaluation were employed. For this evaluation, the cabin atmosphere grab sample analysis data for trimethylsilanol (TMS) and the most commonly observed PDMSs—hexamethylcyclotrisiloxane (D3 siloxane), octamethylcyclotetrasiloxane (D4 siloxane), and decamethylcyclopentasiloxane (D5 siloxane)—were analyzed.

clopentasiloxane (D5 siloxane)—were evaluated for potential correlation with DMSD concentration levels. The samples evaluated were collected in the U.S. Laboratory module during the period between 10 March 2009 and 5 March 2015.

The airborne siloxane concentrations and the DMSD concentration in humidity condensate for the period between 21 June 2011 and 5 March 2015 were plotted on the same graph for visual comparison. It should be noted that only TMS concentrations were quantified during the period between 7 December 2006 and 21 June 2011; therefore, to cover all siloxanes the period after June 2011 was considered. Two humidity condensate samples collected on 6 April 2010 and 12 March 2012 that did not pass laboratory quality control were omitted from the assessment. Figure 1 shows the comparative concentration profiles between siloxane concentrations in the cabin and DMSD concentration in the humidity condensate. The siloxane trend lines are 6th order polynomial data fits. From these profiles, Fig. 1a for D3 siloxane appears to show the greatest potential for correlation with the DMSD concentration in the humidity condensate. Trimethylsilanol, Fig. 1d, follows with the appearance of slight correlation. The trend curves for D4 siloxane and D5 siloxane indicate little to no potential correlation. By visually inspecting data plots, one may conclude that the order of correlation is D3>TMS>D5>D4.

However, visually inspecting graphs can be misleading because correlation must consider closely paired data points. It is difficult to discern correlation merely from visually inspecting trend lines. An analytical approach calculates the Pearson correlation coefficient for paired data points. Using humidity condensate samples dated 15 July 2011, 8 November 2011, 10 September 2012, 20 August 2013, and 3 November 2014 paired with average siloxane concentrations from grab samples acquired within two to three weeks prior to the condensate sample dates, correlation coefficients of 0.95, 0.75, 0.65, and 0.33 are calculated for D4, TMS, D5, and D3 siloxanes, respectively. For the Pearson correlation, a value of +0.7 or higher indicates a very strong positive relationship. The range +0.4 to +0.69 indicates a strong positive relationship, and +0.3 to +0.39 indicates a moderate positive relationship. In this case, the statistical

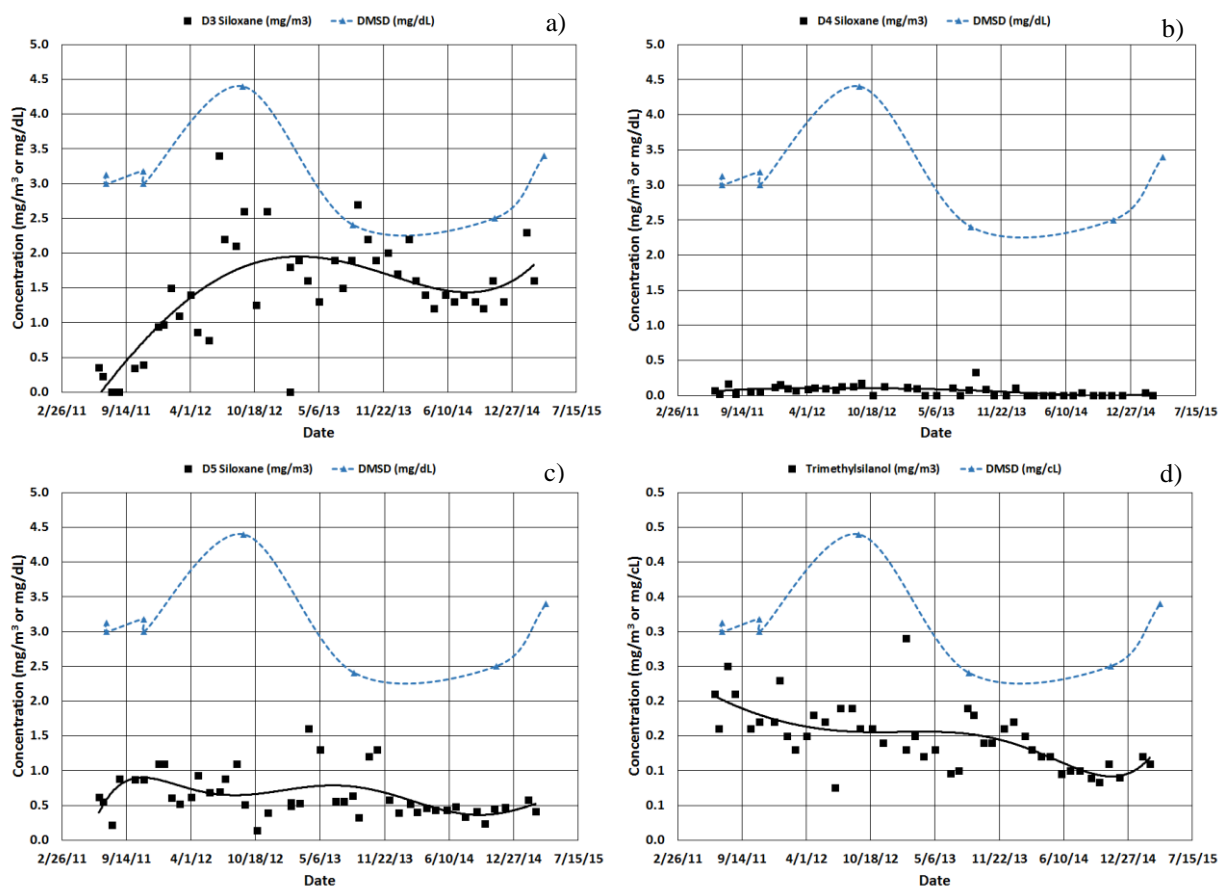


Figure 1. Atmospheric siloxane vs. humidity condensate DMSD concentration trends for the period between 21 June 2011 and 5 March 2015. a) D3 siloxane, b) D4 siloxane, c) D5 siloxane, and d) TMS.

correlation indicates D4 and TMS concentrations in the cabin atmosphere have strong positive relationships with DMSD in the humidity condensate while D5 has a strong positive relationship and D3 has a moderate positive relationship. Statistically, the correlation between siloxane concentrations in the cabin atmosphere and DMSD in the humidity condensate is D4>TMS>D5>D3.

It is very informative to extend this evaluation to consider cabin grab samples and humidity condensate samples collected within 24 hours of each other. Between 10 March 2009 and 29 October 2014 there have been seven sampling events during which a cabin grab sample and a humidity condensate sample were collected within 24 hours of each other. Between 8 August 2013 and 6 February 2016 there have been five AQM sampling events corresponding to humidity condensate sampling events. Due to the lack of data for D3, D4, and D5 concentrations between December 2006 and June 2011, only TMS can be evaluated in this manner. Table 1 shows the sample dates and the respective sample concentrations. The data pairs in Table 1 yield a Pearson correlation coefficient of 0.80 which is a very strong positive correlation. Plotting these data also show a striking visual correlation as shown by Fig. 2. These statistical and visual results indicate that evaluating cabin grab samples and humidity condensate samples very closely in time can provide improved insight into how chemical contaminants in the cabin environment may influence humidity condensate loading.

The TMS concentration in the cabin atmosphere has a very strong positive relationship with D4 and D5 siloxanes with Pearson correlation coefficients of 0.89 and 0.84, respectively. The relationship between TMS and D3 is very weak with a correlation coefficient of 0.13. This indicates that TMS is strongly associated with D4 and D5 offgassing sources. Interestingly, TMS and cyclic siloxanes have been reported as reaction products of linear siloxanes and hydroxyl radicals.¹ These relationships are informative since TMS as well as DMSD and to a lesser extent monomethylsilanetriol (MMST) are decomposition products of linear and cyclic PDMS species as they degrade toward CO₂ and SiO₂ products. Trimethylsilanol can also react with hydroxyl radicals in the gas phase to form CO₂ and SiO₂ products as well as reaction intermediates that include DMSD and MMST.^{2,3} The decreasing volatility and increasing affinity for water of the

Table 1. Cabin grab sample and humidity condensate samples collected within 24 hours of each other.

SAMPLE DATE	CABIN TMS (mg/m ³)	CONDENSATE DMSD	
		(mg/cL)	(mg/L)
3/10/2009	0.35	0.305	30.5
7/17/2009	0.28	0.19	19
9/3/2009	0.14	0.168	16.8
10/19/2010	0.56	0.5945	59.45
3/15/2011	0.37	0.531	53.1
11/8/2011	0.17	0.309	30.9
8/20/2013	0.25*	0.25	25
10/29/2014	0.11	0.25	25
11/3/2014	0.30*	0.25	25
4/6/2015	0.35*	0.34	34
10/29/2015	0.60*	0.49	49
2/6/2016	0.30*	0.35	35

AQM cabin concentration measurement.

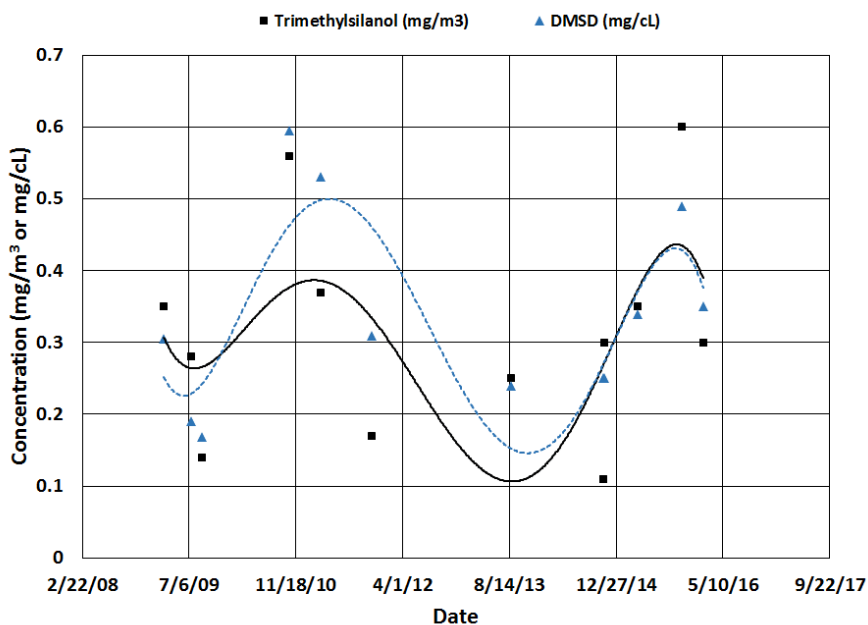


Figure 2. Trimethylsilanol and DMSD concentrations for samples collected within 24 hours of each other. Solid trend line is TMS and dashed trend line is DMSD. Both are 5th order polynomial fits.

silicon-containing products such as DMSD and MMST can lead to removal from the cabin atmosphere before complete conversion to CO_2 and SiO_2 .⁴ Trimethylsilanol can also oxidize in the liquid phase.⁵ These phenomena can account for the strong relationship between the TMS concentration in the cabin atmosphere and DMSD concentration in the humidity condensate illustrated by Fig. 2. Because TMS has a vapor pressure very close to that of water, it can evaporate from the liquid phase.⁶ It is plausible that trimethylsilanol evolution from the liquid phase as it is produced along with DMSD by D4 and D5 degradation on condensing heat exchanger surfaces could influence the cabin concentration. As well, TMS reaction in the liquid phase to DMSD may also explain why TMS is rarely reported in humidity condensate sample analyses. Overall, on considering the reported reaction and volatility phenomena associated with PDMS species toward complete conversion to CO_2 and SiO_2 in both the gas and liquid phases, the strong correlation relationships between TMS, D4, D5, and DMSD can be expected.

III. ISS Siloxane Scrubber Filter Development

An initial trade study evaluating the various design factors was performed to identify the most viable design concept for siloxane removal. Factors considered in the trade study included design cost, crew time required for maintenance, resupply mass, and siloxane removal performance. The primary concepts considered included the following options:

- Adding a siloxane scrubber to the inlet of each ISS Bacteria Filter Elements (BFE). This approach would require a unique design solution for each location and complicate crew training for maintenance.
- Adding a standalone siloxane scrubber separate from the ISS BFEs. This approach is desirable to achieve an overall reduction in atmospheric siloxanes, but does not provide direct protection for individual Common Cabin Air Assembly (CCAA) CHXs. In addition, there is limited volume available on ISS for additional environmental control and life support (ECLS) systems, and limited acoustics margin to accommodate an additional fan.
- Installing siloxane scrubbers only in the four Node 1 BFE locations. This approach is desirable to achieve an overall reduction in atmospheric siloxanes, but does not provide direct protection for individual CCAA CHXs.
- Replacing the existing ISS BFE filters with a combination filter media and siloxane scrubber. This approach addresses the desire to provide individual protection for each CCAA CHX but also requires a significant resupply mass to replace the twenty-one BFEs currently aboard ISS.

The ground rules and assumptions for the trade study included effective removal of siloxanes, a duration of filter change out of at least twelve months, and minimal impacts to on-orbit crew operations. A weighted rating system was used to rate the implementation options against performance, project, crew time, and logistics. Factors for performance included effective removal of siloxanes, ISS coverage area, time between media change out, reliability, and channeling, sealing, and potential for flow bypass. Key factors for the project included technical risk, schedule risk, recurring costs, and non-recurring costs. Crew time factors included an assessment of initial installation and recurring maintenance. Logistics and re-supply considered installation locations, on-orbit stowage volume, launch vehicle limitations, launch weight, and return/refurbishment versus single use.

This trade study ultimately determined the preferred solution is to replace the twenty-one BFEs aboard ISS with a modified filter that incorporates both filtration media (to meet ISS particulate requirement) and an adsorbent media, Amborsorb 4652, for siloxane removal. Amborsorb 4652 was selected because it provided superior siloxane adsorption capacity relative to the other media. However, once the design concept began formulation, engineering personnel determined that the pressure drop associated with Amborsorb 4652 was not viable for this location. The pressure drop associated with Amborsorb 4652 would require a significant increase in fan speed, which would violate module-level ISS acoustics requirements that are already at their limits. Therefore, the design concept was modified to use Cabot Norit GCA 48 granular activated carbon which provided measurably more siloxane capacity for the same pressure drop compared to Amborsorb 4652, as shown in Fig. 3.

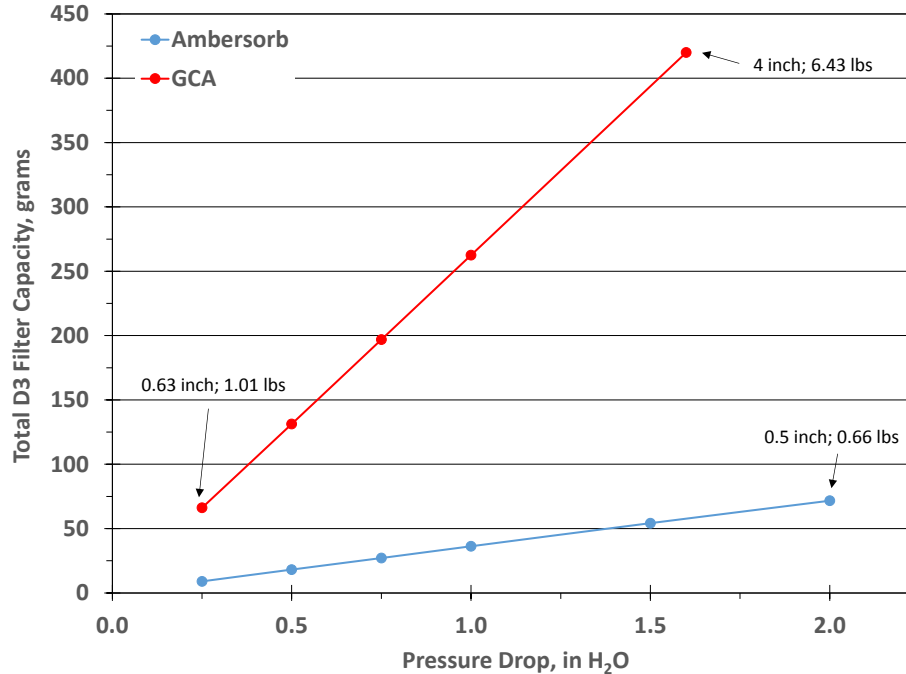


Figure 3. Estimated total filter capacity for D3 siloxane as a function of allowable pressure drop estimated by Ergun equation at 50 CFM flow. Displayed are filter depths and estimated media weight for select data points. Ambersorb bulk density 0.37 g/mL; sieved to mean particle size of 531 μm . GCA bulk density 0.45 g/mL; mean screen size of 3.57 mm. Partial pressure adjusted (Poylani potential energy adjusted) media D3 capacities taken to be 288 mg/g (Ambersorb) and 144 mg/g (GCA). Filter cross sectional area taken to be 0.0638 m^2 .

IV. Siloxane Scrubber Filter Design and Testing

A prototype filter was constructed to test a full scale PDMS removal filter for associated pressure drop, acoustics impact, and filter efficiency. During bench scale testing at Kennedy Space Center (KSC), basic adsorption characteristics were eluded. However, further development was warranted to fully characterize the new PDMS removal filter approach. The PDMS prototype filter was tested under the same prescribed test procedures and utilized the same test hardware as the current High-Efficiency Particulate Arrestance (HEPA) filters aboard the ISS. The exception was the HEPA filter efficiency testing, which was conducted at Glenn Research Center (GRC). The outcome of this test activity was relevant data required for selecting optimal filter concepts to further develop the flight PDMS removal filter. In addition to the prototype testing, a high level flight concept of the next generation PDMS removal filter was generated. This concept looked to address issues with cargo manifesting and direct HEPA filter replacement aboard the ISS.

A. Prototype Filter Options

The results of the PDMS adsorption studies at KSC demonstrated that very few selected adsorbents from the trade study showed an efficacy to remove PDMS from the ISS simulated atmosphere. The two candidates that showed the greatest adsorption characteristics for PDMS were a graphite-based adsorbent, Ambersorb 4652 and a coconut shell-based granular activated carbon, Cabot Norit GCA 48. However, due to high pressure drop values associated with the Ambersorb 4652, GCA 48 was selected for 5h3 flight design. Also, due to its favorable adsorption characteristics for PDMS and commercial availability, GCA 48 was also selected as the material utilized in the Node 1 BFE locations in the first generation PDMS filters installed in May 2015. These filters utilized four Cabin Air Catalyst Element Assemblies (CACEA) containing GCA 48 activated carbon. This location was appropriate because there are no CHX units present, and therefore no requirement for HEPA-rated filtration. The CACEA shown by Fig. 4 utilizes a bag containment approach for the GCA 48. This air-permeable fabric bag is filled with GCA 48 and placed in the CACEA housing, after which additional hardware is used to compress the bag to limit GCA 48 from shifting and creating bed

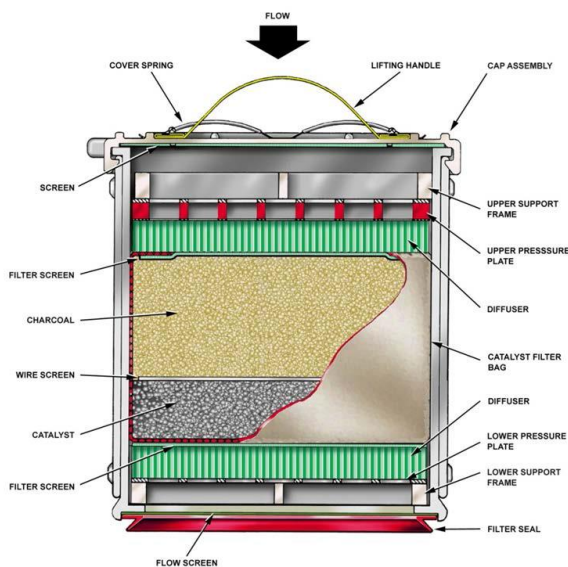


Figure 4. Cabin Air Catalyst Element Assemblies cross section.



Figure 5. Preformed aluminum honeycomb for adsorbent containment.

channeling in the filter housing. This additional hardware takes up considerable volume in the CACEA housing, limiting the ability to maximize adsorbent packing.

The prototype PDMS removal filter utilizes an approach that would eliminate the need for the bag and compressive loading design. The prototype filters took advantage of preformed aluminum honeycomb structures shown in Fig. 5 to contain the GCA 48 activated carbon. The honeycomb allows the adsorbent material to be packed into the individual pores of the structure. This limits the ability of the adsorbent to move in the horizontal plane, which eliminates significant attrition and bed channeling.

More importantly, the honeycomb structure does not require a compressive load to maintain adsorption bed integrity. The honeycomb pores in essence create multiples of smaller beds that are contained individually. The structure does utilize a portion of the available filter envelope, but it is minimal compared to the volume occupied by the fabric bag and compressive load hardware in the CACEA configuration.

In addition to identifying a more efficient adsorbent containment approach for the prototype PDMS removal filter, the requirement to still meet a HEPA-rated filtration capability remained valid. This is ultimately accomplished by retaining HEPA-rated filter media in the prototype design. However, the filter media depth must be decreased to accommodate the addition of the GCA 48 adsorbent. The impact of decreasing the filter media depth on particle removal efficiency was further investigated. The current ISS BFE utilizes a 10.2-cm depth to meet the filtration requirement. By reducing the filter media depth, the filtration surface area decreases while the process air flow velocity increases which would cause a possible pressure drop impact. At the nominal ISS BFE filter flow rate of 1.98 m³/minute a 5.08-cm filter media depth was deemed adequate. Two filter manufacturers supplied 5.08-cm deep HEPA-rated media filters for prototype testing as well as a 4.13-cm deep filter.

With the initial requirements of the PDMS prototype filter defined, the following configurations were constructed for evaluating pressure drop, acoustics, and filter efficiency. In addition to configurations containing a carbon bed and HEPA-rated filter, a 10.2-cm deep packed bed was also constructed to evaluate granular media's ability to achieve HEPA-rated filtration performance.

Table 2. Selected Prototype Filter Configurations

FILTER OPTION	ADVANTAGES	DISADVANTAGES
10.2 cm HEPA Filter**	Current State	No PDMS Removal Capacity
5.08 cm GCA 48 bed/5.08 cm HEPA	PDMS Removal/HEPA	Minimum Carbon Volume
>5.08 cm GCA 48 bed/<5.08 cm HEPA	PDMS Removal/HEPA	May not meet HEPA Rating
10.2 cm GCA 48 bed	PDMS Removal/Long Life	May not meet HEPA Rating

B. PDMS Prototype Filter Construction

The PDMS prototype filter design was based around the current Catalyst Element housing. Utilizing this empty housing as the design envelope allowed for the use of existing test equipment to determine pressure drop, acoustics and filter efficiency. The CACEA housing is dimensionally identical to the current BFE filter housing used aboard ISS. Additionally, due to multiple prototype filter configurations being tested, an additional filter housing was required to facilitate testing. This extra prototype filter housing was obtained from a scrapped flight BFE filter. In order to utilize this housing, the filter media was removed and the housing was cleaned of all residual adhesive and reassembled for use.

The honeycomb material utilized in the PDMS prototype filter was procured from Plascore Inc. Two depths, 2.54 cm and 5.08 cm, were evaluated for the prototype design. The 5.08 cm honeycomb was selected for use in the development of both the 2.54-cm and 5.08-cm carbon beds. The honeycomb structure was cut to fit to the internal dimensions for the CACEA and BFE housings. Once the honeycomb was cut to size, a bottom containment screen was fitted and attached to the outer surface. Once the bottom containment screen was attached, the filter could be loaded with GCA 48. Prior to loading the GCA 48, the material was sieved to remove any dust and small particles. The GCA 48 was loaded simply by gradually pouring the granules over the top of the filter. The material flowed smoothly into the pore volumes of the honeycomb and required minimal vibration to settle. Once the 2.54-cm and 5.08-cm PDMS Removal filters were full, the top containment screens were attached and the filters were sealed closed. The respective GCA 48 volumes for each filter were recorded as 3200 cm³ for the 5.08-cm and 6400 cm³ for the 10.2-cm depths.

C. HEPA Filter Media

The HEPA filter media utilized in the PDMS prototype filter testing were supplied by Flanders Filtration and Cambridge Filters. Both of these vendors supply various commercial and industrial filters for a variety of applications. Flanders currently manufactures and supplies the U.S. and Japanese filter elements for ISS. These filters are nonwoven borosilicate-based pleated media that provide the HEPA rating of 99.97% retention of particle 0.3 µm or larger. The test article Flanders provided was comprised of the same material used aboard ISS. The media provided by Cambridge was also HEPA-rated but are constructed from polytetrafluoroethylene (PTFE). The PTFE filters are advertised to provide no offgassing and lower pressure drop than the conventional borosilicate fiber filters. Cambridge provided two PTFE HEPA filters—a 5.08-cm and 4.13-cm depth. Cambridge did indicate that the 4.13-cm deep filter would not provide HEPA-rated filtration due to the high velocities through the filter. Instead this filter would provide 99.9% versus the HEPA standard of 99.97%. For testing purposes this was deemed acceptable, as an investigation into the efficiency of the PDMS removal beds ability to aid in filtration was planned to be evaluated during HEPA efficiency testing. To complete the prototype filters, the HEPA portion of the filter was placed in the bottom of the CACEA housing followed by the honeycomb filled with GCA 48.

D. Prototype Filter Testing

Following the completion of the PDMS removal prototype filters, the units were tested for pressure drop and acoustics in the United Technologies Aerospace Systems (UTAS) Acoustics Laboratory. In order to conduct this testing, heritage test hardware specifically developed to test and qualify the ISS BFEs was re-assembled in the lab. During previous acceptance testing of the BFEs for ISS, testing was conducted outside of the acoustics lab at UTAS. Bringing the test hardware into the acoustics lab presented a challenge as no ancillary equipment was available to provide facility airflow required to test the filter configurations. To provide the needed airflow, a flight cabin fan available at UTAS was utilized. This hardware provided variable speed airflow and interfaced seamlessly with the test setup. A schematic and test set up pictures from the Acoustics Laboratory at UTAS are displayed in Figs. 6 and 7.

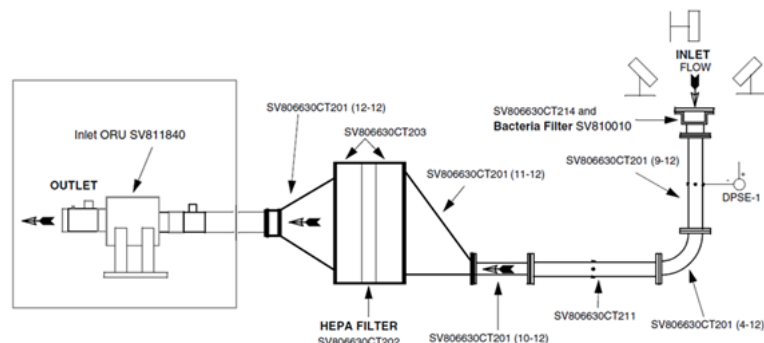


Figure 6. Schematic of the prototype PDMS removal test rig.



Figure 7. Views of the pressure drop and acoustics testing rig.

E. Prototype Filter DP Results

The testing procedures developed for the pressure drop and acoustics testing were based on historical acceptance test procedures for the current ISS BFEs. Pressure drop is an acceptance criteria for the BFEs, however acoustics is not and has never been evaluated for the BFEs. The pressure drop acceptance test on the current BFEs is to run the filter elements at a minimum flow rate of $1.89 \text{ m}^3/\text{minute}$ and observe no more than a maximum pressure drop of 82.2 Pa ($0.33 \text{ inch H}_2\text{O}$). For the prototype testing, the nominal flow rate of $1.89 \text{ m}^3/\text{minute}$ was evaluated in addition to a flow rate of $2.83 \text{ m}^3/\text{minute}$. This additional flow was evaluated to elucidate data on the overall impacts on both pressure drop and acoustics and could prove beneficial to future ISS operation if an increased flow rate is ever desired. The results from the pressure drop testing are displayed in Fig. 8.

In most cases, at the nominal flow rate of $1.89 \text{ m}^3/\text{minute}$, the pressure drop of the tested configurations stayed below 249 Pa ($1 \text{ inch H}_2\text{O}$). The exception was with the 5.08-cm Cambridge HEPA filters, both of which had a pressure drop slightly above 249 Pa . This higher pressure drop was a result of a smaller filter surface area on the Cambridge HEPA filters. The surface area was smaller due to the large housing frame used in the filter construction. The Flanders HEPA filters had a very small supporting housing and larger surface area. In addition to the tested filter configurations, i.e. Carbon/HEPA, each individual sections was also evaluated for pressure drop and acoustics. An observation from this testing was that the individual filter sections pressure drop did not cumulatively match the paired sections pressure drop. In all cases the paired pressure drop of the filters sections was larger than the combined individual pressure drop for the sections. This indicates that there is some additional pressure drop attributed to combining the filter sections together. This small gain could be attributed to a combined effect from each sections frame material such as screens, housings, etc.

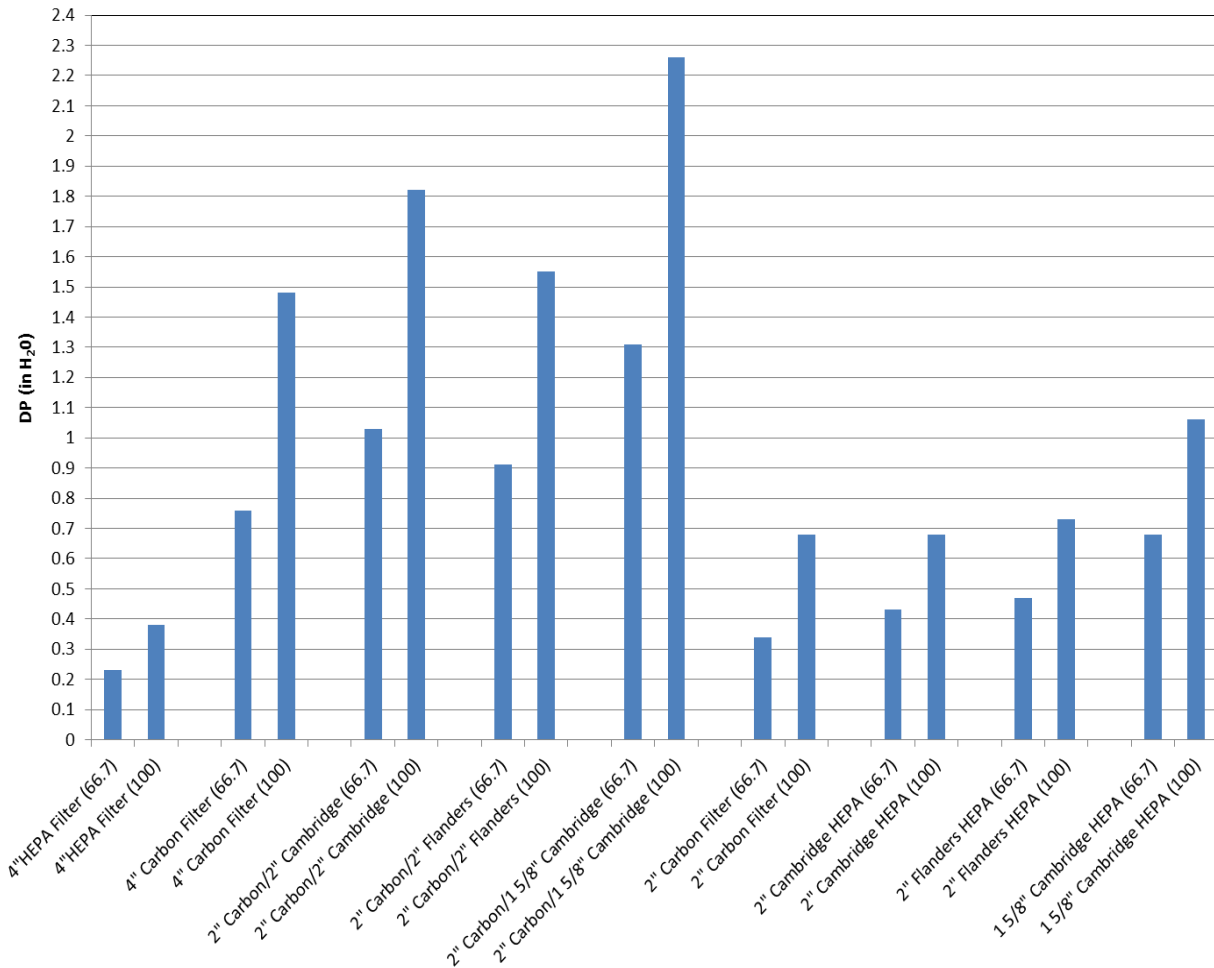


Figure 8. Pressure drop results for various prototype PDMS removal filter configurations.

V. PDMS Removal Filter Flight Concept

During the development of the full scale PDMS removal filters, concepts of what the actual flight filter might evolve into were evaluated. One of the primary drivers is that the PDMS filter would need to be a direct replacement for the BFE. The filter would be required to fit into the existing BFE housing aboard ISS and still provide HEPA-rated filtration performance. An additional aspect to the concept PDMS filter was the ability to manifest the filter on the new generation of launch vehicles. A concern had arisen on previous resupply mission to ISS, where the BFEs were too large to be efficiently packed into the vehicle. The current HEPA filters require an M Cargo Transfer Bag (CTB), which is a large bag that is difficult to manifest. In order to efficiently manifest the new PDMS removal filters onto the current resupply vehicles, it was proposed that new filters be a pod type concept. This pod concept would effectively divide the new filters length in half, allowing the filters to fit into a single CTB. This would allow for greater flexibility when manifesting and packaging the filters for ISS resupply. The pod concept provided unique challenges to developing a new filter design. The primary issue was with the sealing mechanism for the filter. The current BFE has a lip seal that effectively seals the filter at the bottom of the filter housing aboard ISS. By dividing the filter in half, a leak path would be created between the two pods. This leak path would need to be addressed with a new seal concept that would prevent bypass flow between each of the filters. Three seal solutions were traded during the development of the filter concept, a bottom seal, a radial seal and a top seal. It was ultimately determined that the most feasible approach for the flight concept would be the top seal solution. The top seal provides the advantages of acting as a seal, top cap and filter positioning element all in one. While the top seal is larger than the two other options, its thin profile will allow it to be easily manifested on resupply missions to ISS. A complete model of the filter concept is shown in Fig. 9.

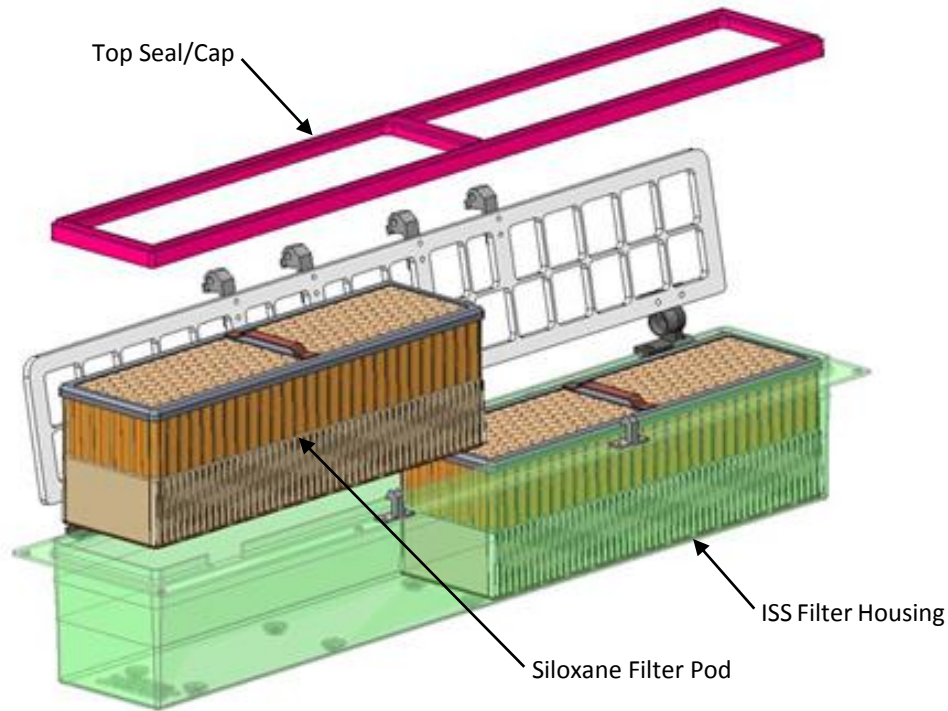


Figure 9. PDMS removal filter pod concept.

The preliminary assembly approach of the filter would be to have a single housing that contains all the elements of the filter. The HEPA filter would be bonded in place to the frame using a similar approach utilized in the BFEs. The HEPA filter and honeycomb containment structure would be separated by a screen and a thin compressible foam layer. This foam layer will add a small amount of compression to honeycomb segment to eliminate any movement of the granular carbon caused by the irregular shape of the material. During prototype filter development, it was observed that the irregular shape of the carbon material would impede the screen from sitting flat on the honeycomb structure. This allowed for some void volume to develop between the screen and honeycomb, which allowed for a small amount of material shifting in the honeycomb bed. To address this issue, a thin compressible foam layer will occupy this volume to eliminate the material shift. This containment approach will also be repeated on the top of the honeycomb section prior to the closure screen.

The flight concept model captures the high level detail of the filter design, but does not elucidate information to the possible issues associated with a production filter. A list of the critical factors that will need to be addressed in the further development of a PDMS removal filter are detailed in Table 3. It is anticipated that these factors will be fully explored in a follow on CR focused on filter development.

Table 3. List of Critical Design Factors for Flight PDMS Filter Development.

CRITICAL FACTOR	DESCRIPTION
Filter Requirements	Final PDMS filter requirements will drive production schedule
Launch Loads	Required launch loads will impact filter design and ability to package in CTB
Carbon Fine Generation	Address fine generation and impact on HEPA filter life
HEPA Filter Selection	Material selection and filtration efficiency
Carbon Preparation	Define carbon washing procedure prior to packing
Carbon Packing Procedure	Develop procedure for honeycomb packaging
Screen and Foam Selection	Optimum selection of screen and foam for carbon containment
Seal Design	Material selection for seal design

A. Particulate Removal Efficiency and Pressure Drop Testing

As part of the evaluation process, all the siloxane scrubber/hybrid filter prototype configurations were tested to determine if they meet the particulate removal efficiency and pressure drop requirements for the preset ISS BFEs that they are designed to replace. The penetration efficiency requirement for the ISS BFE is 99.9% at 0.3 microns at a volumetric flow rate of 1.98 m³/minute (70 ft³/minute).⁷ The efficiency testing was performed in GRC's Particulate Filtration Laboratory, equipped with a customized test apparatus specifically designed to test the integrity and particulate removal efficiency of the present ISS BFEs. A secondary objective was also measure pressure drop to compare with the measurements made in conjunction with the acoustic testing of the same hybrid filter prototypes at UTAS.

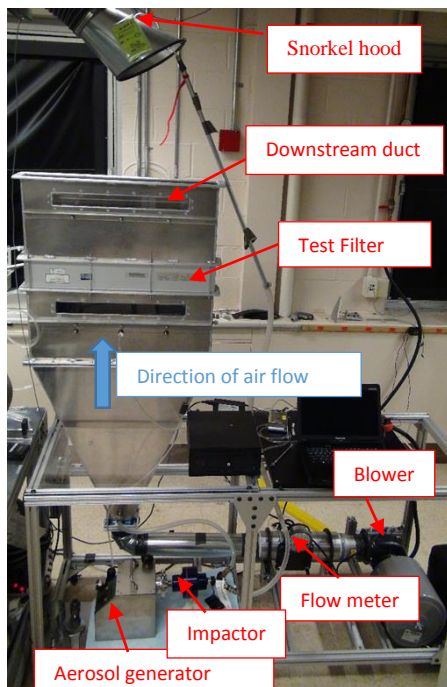


Figure 10. Filtration test setup.

1. Experimental Setup/Method:

An annotated photo of the experimental setup and test rig is shown in Fig. 10. The test setup utilizes a “blow-down” configuration, i.e. the blower is mounted upstream of the test article. Details of the experiment rig and verification of flow uniformity and aerosol distribution in the test duct are described in Ref. 8, but several modifications were made to upgrade the test rig for filter leakage testing, for particulate removal efficiency testing. The modifications include a higher flow rate blower to meet flow requirements for the higher pressure drop expected from the hybrid filter configurations, an impactor attachment to the Laskin aerosol generator to achieve a revised aerosol distribution in order to meet the filtration test standard, downstream duct to capture exit flow from the test article, a venturi meter to measure flow, and pressure transducers to measurement pressure drop across the test article.

Polyalphaolefin (PAO) was used as the challenge aerosol. The aerosol was generated via a Laskin nozzle generator with an impactor attachment, and injected into the test duct upstream of the test article; the

PAO concentration at the filter inlet was 10-20 mg/liter. The output measurement of the photometer is penetration in percent of upstream aerosol concentration. The aerosol generator produces a tightly controlled particle size distribution with mass mean diameter of 0.303 microns. In total, four hybrid filter configurations and a standard ISS BFE were tested; a total of twenty separate tests were performed.

2. Test Results

Penetration measurements were made by slowly scanning across the length of the filter inside the downstream duct approximately 10.2 cm to 12.7 cm from the exit surface of the test article; a scan in the reverse direction was performed immediately after the first scan for repeatability purposes. For all configurations except the ISS BFE, slightly higher penetration values were observed at each end and low penetration in the middle. This pattern is not uncommon in industrial testing, and is presumably due to the filter edge seals, which will certainly be improved in a more mature filter design. Data were averaged and efficiency computed simply by subtracting average percentage penetration from 100%. The particulate removal efficiency testing results are shown in Table 4. Values in the penetration and efficiency columns in Table 4 represent the average values in the mid-section whereas values in parentheses are averaged across the entire filter. All prototype configurations did meet or exceed the ISS BFE efficiency requirement of 99.9%, except for the 10.2-cm deep activated carbon filter configuration.

The pressure drop measurements (provided in Table 4) were similar to those obtained during the acoustic testing at UTAS. According to the ISS BFE design specification, a clean unused BFE is designed to have a pressure drop no more than 82.2 Pa (0.33 inches H₂O) at a flow rate of 1.88 m³/minute (66.7 ft³/minute); at the end-of-life, the BFE pressure drop should not exceed 124 Pa (0.5 inches H₂O).⁷ Under normal cabin ventilation blower speeds, the cabin ventilation velocity begins to degrade at 174 Pa (0.7 inches H₂O). The BFE end-of-life pressure drop specification, therefore, provides about 28% operational margin for maintaining cabin ventilation velocities under nominal conditions. The pressure drop for all siloxane scrubber hybrid prototype configurations was significantly higher than a used BFE and in some instances exceeds the end-of-life specification. This is not unexpected as these configurations have a reduced HEPA filter media surface due to the 5.08-cm reduction in media depth, plus the added resistance due to the 5.08-cm porous scrubber portion. Operating the cabin ventilation blower at a higher speed can compensate for the increased pressure drop. Acoustic testing indicated that it is acceptable to operate the ISS ventilation blowers at higher

speeds to accommodate the hybrid filter element design. Data for the Cambridge HEPA filter tended to increase in pressure drop when checked after the penetration tests, and is likely due to loading from the challenge aerosol (see asterisked values in Table 4). The Cambridge filter media is an expanded polytetrafluoroethylene (ePTFE) membrane that is more susceptible to loading from oil-based aerosols. The test configurations with the Flanders filters did not see any measurable change in pressure drop during our limited testing. Total time that each configuration was exposed to the challenge aerosol was recorded in case further analysis of loading characteristics is desired. In all tests of hybrid configurations, i.e. with a 5.08 cm (2 in.) HEPA filter, met or exceeded the 99.9% BFE filtration efficiency requirement. For the 10.16 cm (4 in.) carbon filter, the challenge aerosol appeared to pass through the filter unimpeded and offered little or no filtration performance. Test was abruptly terminated before a measurement was recorded to limit exposure of test personnel to the unfiltered aerosol. Lastly, note that several of the test points at higher flow rates reached less than the desired 2.83 m³/minute (100 cfm) in our test setup, due to the increased test article resistance.

Table 4. Prototype siloxane scrubber particulate removal efficiency and pressure drop results. Pressure drop values with asterisks were measured after exposure to challenge aerosol during filter efficiency testing.

CONFIGURATION	FLOW RATE		PRESSURE DROP		AVERAGE PENETRATION (%)	AVERAGE EFFICIENCY (% , CALC)
	(cfm)	(m ³ /min)	(inches H ₂ O)	(Pa)		
2" Cambridge HEPA (only)	66.5	1.88	0.51/0.69*	126.9/171.7*	0.0248	99.9752
2" Cambridge HEPA (only)	100	2.83	0.79/0.91*	196.6/226.4*	0.0284	99.9716
2" Cambridge/2" Carbon	66.5	1.88	1.08	268.7	0.0318	99.9681
2" Cambridge/2" Carbon	85	2.41	1.53	380.7	0.0309	99.969
2" Flanders HEPA (only)	66.5	1.88	0.54	134.4	0.0080	99.9920
2" Flanders HEPA (only)	100	2.83	0.82	204.0	0.0126	99.9874
2" Flanders/2" Carbon	66.5	1.88	1.01	251.3	0.0022	99.9978
2" Flanders/2" Carbon	85	2.41	1.37	340.9	0.0103	99.9897
2" Flanders/2" Carbon	85	2.41	1.40	348.4	0.0096	99.9904
4" Charcoal (only)	66.5	1.88	0.86	214.0	Near 100% penetration; terminated test w/o measurement.	-
ISS BFE (EDU)	66.5	1.88	0.23	57.2	0.0221	99.9779

VI. Siloxane Scrubber Filter Implementation in Node 1

Four Node 1 scrubbers were installed in April 2015. These scrubbers provided an immediate decrease in ISS cabin siloxane concentrations based on the Air Quality Monitor (AQM) measurements, which includes detection of D3, D4, D5, and TMS. Figure 11 shows D4 siloxane is removed effectively to its detection limit of 0.05 mg/m³, with an excursion in September 2015 due to a vehicle docking. D5 siloxane and D3 siloxane have also each been reduced to less than 1.5 mg/m³ and 1 mg/m³, respectively. Trimethylsilanol has been gradually increasing as it has the lowest affinity for the GCA 48 and is therefore slowly saturating the adsorbent. Despite the excellent performance of the Node 1 scrubbers the DMSD concentration in the condensate has not decreased based on samples taken in the last year, as shown in Fig. 12. Engineering personnel are reviewing this data to determine if this result indicates the PDMS filters will not provide the desired reduction of DMSD in the condensate. However, this investigation is ongoing and beyond the scope of this paper.

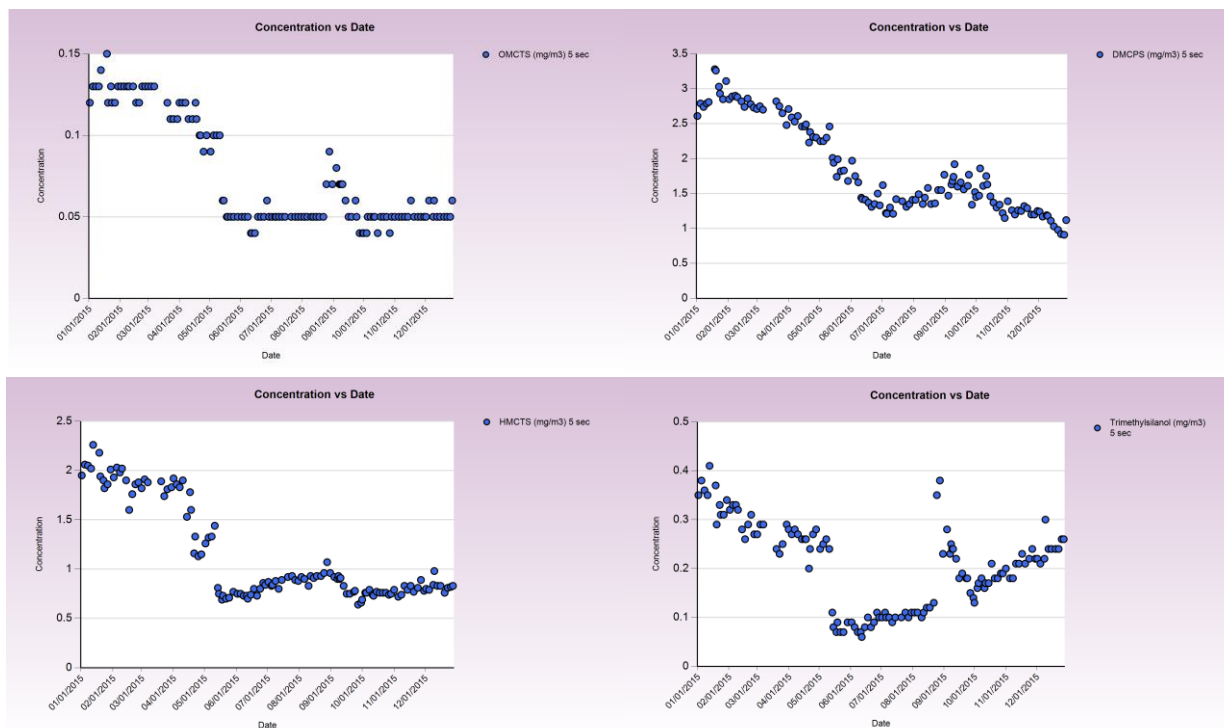


Figure 11. ISS AQM results for various siloxanes in 2015.

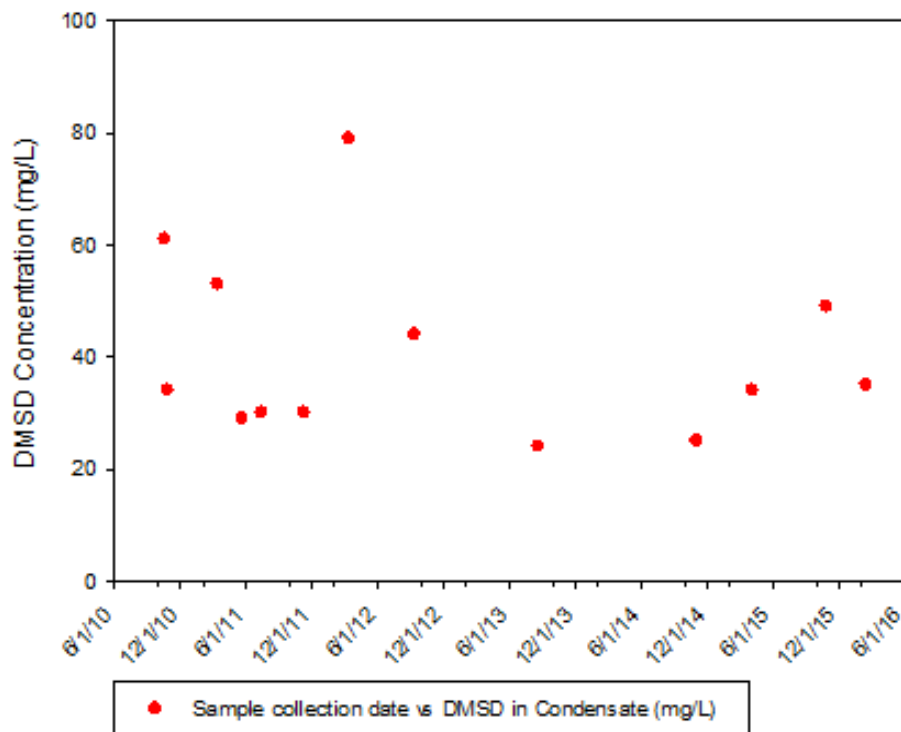


Figure 12. DMSD Concentration in ISS humidity condensate.

VII. Conclusion

An extensive effort is ongoing to develop a means to filter PDMSs in the air upstream of the ISS CHX units based on the theory that PDMSs are decomposing to DMSD on the heat exchange coating. Ground tests have determined the optimal design configuration is to modify the existing ISS BFEs with a design that implements 5.08 cm of packed adsorbent (GCA 48 activated carbon) and a 5.08-cm deep HEPA media filter. Development of the flight hardware delivery is pending final authorization by the ISS Program with an expected delivery date of 14 months.

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